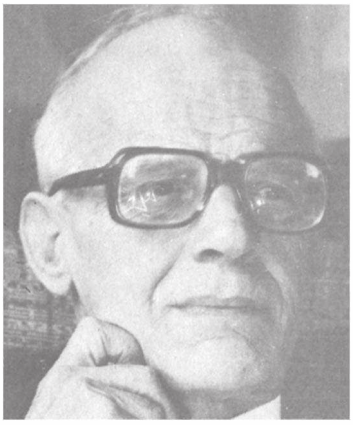
Lord Kelvin demonstrated

J. T. LLOYD



J. T. Lloyd *was awarded an honorary degree by Glasgow University in 1961 for his work on particle accelerators and detectors and for his services to the Kelvin Museum. He is well known for his lectures on Lord Kelvin. He has also exhibited his own inventions including the speaking speedometer which can be adapted to read all units and which may be used in the future by blind science students.* *(Department of Natural Philosophy, The University of Glasgow, Glasgow, G12 8QQ, Scotland)*

If we consider the 660 papers written by Lord Kelvin in his lifetime (see histogram, Fig. 1), and the enormous amount of work represented by these papers, and if we consider his large commercial interests, his consultancies, his public lectures, his involvement in public inquiries, even the reception of a uniquely large number of honors, we might well ask – how could he also be a teacher?

The remarkable thing is that he, one of the busiest men who ever lived, was first and foremost a teacher. As the son of a professor, educated by professors from childhood, and living within the precincts of the university for most of his life – including his 53 years as professor of natural philosophy – it was quite ingrained in him that his main priority was the teaching of the young. His is an outstanding example of the university system, for while we can point easily to his many material achievements in the realm of science, we can also point to the thousands of students who were educated by him and to the subsequent value to the world caused by the spread of his high ideals of scientific attitude and integrity.

As a basis for a sound understanding of physics Kelvin always said that there must be a fluent mathematics, a knowledge of mechanics and dynamics, and an awareness of the importance of measurement. But there was also another prerequisite – the knowledge of the language necessary to assimilate other peoples' writings and to express oneself adequately. In the year of his death, 1907, Kelvin observed – "A boy should have learned by the age of twelve to write his own language with accuracy and some elegance; he should have a reading knowledge of French, should be able to translate Latin and easy Greek authors, and have some acquaintance with German. Having studied thus the meaning of words, a boy should study logic."

His own childhood was of exceptional interest. Born as William Thomson, in Belfast on 26th June, 1824, the Irish loquacity acquired in his infancy was strongly tempered by the caution inherited from his predominantly Scottish ancestry. Except for a short period at a writing school William was educated entirely at home, mainly by his father and eldest sister. We can picture him from a description in Agnes King's book – *Kelvin, the Man* – as a child of four, dressed in his baby clothes, sitting on a table with celestial and terrestrial spheres, listening to his father describing the wonders of astronomy (his father having risen at 4 a.m. to work on one of the books he was writing). In 1830 William's mother died, leaving a family of seven, and in 1832 James, the father, took his young family to Glasgow, on his appointment as professor of mathematics at Glasgow University. Almost immediately William commenced taking classes at the university, but unofficially. We have a description of this little fairhaired boy attending lectures on logic, Greek, moral philosophy, etc., surrounded by students twice his age. At the age of ten William matriculated as a student proper, and won many prizes during his five years in Glasgow. He then became a student at Cambridge University for a further five years. In 1846, at the age of 22, William Thomson was appointed professor of natural philosophy at Glasgow University.

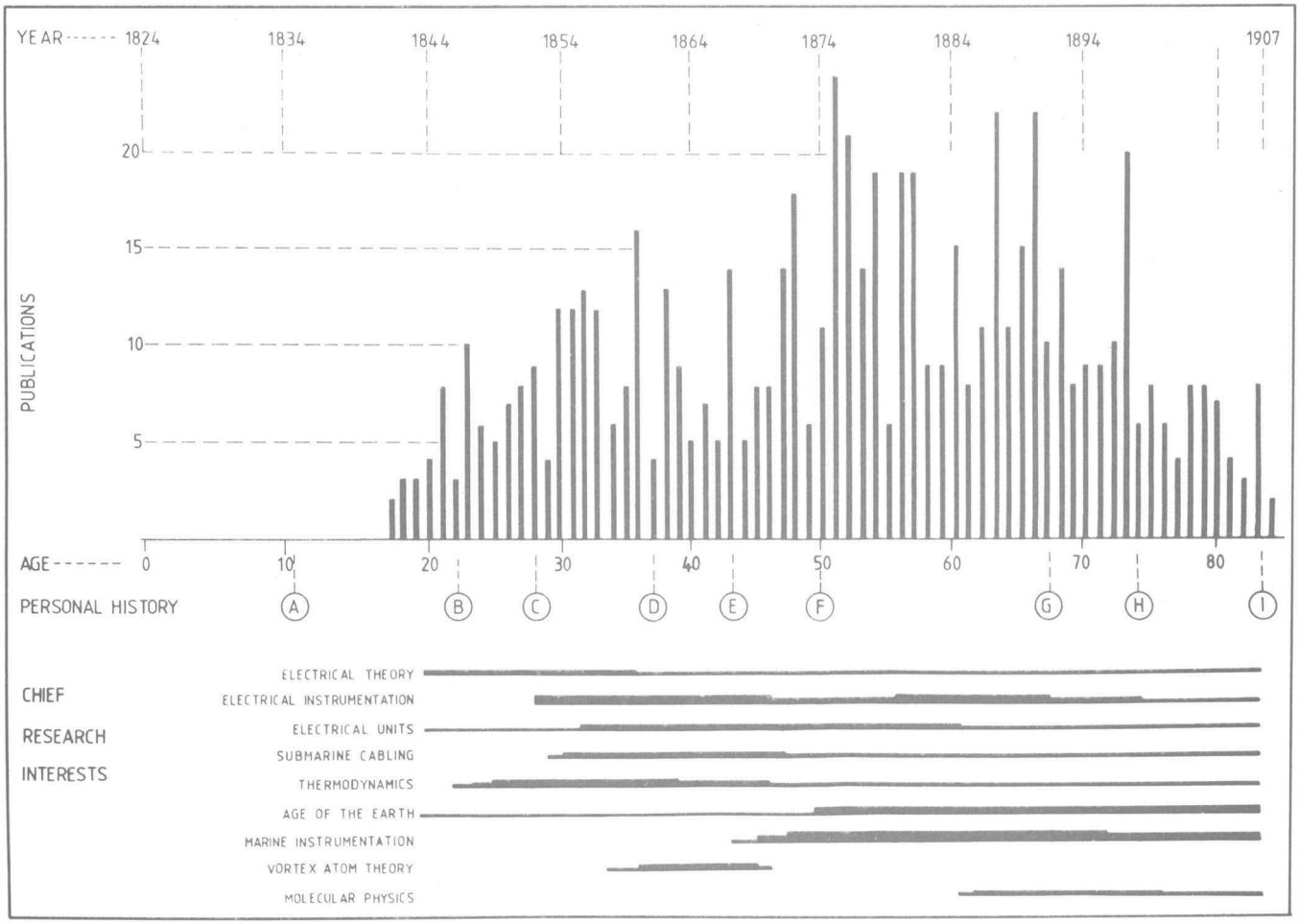


Fig. 1. The life of Lord Kelvin. A) Matriculation. B) Chair. C) First marriage. D) Serious injury. E) Knighthood. F) Second marriage. G) Peerage. H) Retiral from Chair. I) Death.

I would like now to give a glimpse of his antecedents in this ancient office. Physics teaching commenced in the university at the Foundation, in 1451, and it was undertaken by "regents" until the first "professor" was appointed, in 1727. One of these regents, of whom we know a good deal, was George Sinclair, Regent from 1654. Sinclair was an expert on hydrostatics, and in one of his books on astronomy he wrote: "God is not tied to numbers; yet nevertheless he doeth and disposeth his Works by Number, Weight and Measure." This fairly represents Kelvin's own attitude. John Anderson, professor from 1757 to 1796, gave classes for many years to artisans from the town. He is held to be a pioneer of education for the working man. When Anderson became professor there was attached to the university an instrument maker who was to be one of the greatest engineers who ever lived – James Watt. While Watt was repairing the model Newcomen engine belonging to the department he invented the "separate condenser." This so improved the efficiency of steam engines that this invention is believed to have marked the beginning of the Industrial Revolution. With these predecessors one can better understand Kelvin's intensely practical attitude to science teaching, one can appreciate his favorite saying – "If I can make a mechanical model of a thing I can understand it."

The 19th century was, of course, a remarkably fecund period in physics. The new sciences of current electricity and thermodynamics, in particular, were hanging like ripe fruit and it was Kelvin who garnered much of the harvest. Current electricity had emerged suddenly and unexpectedly in 1790. By 1830 most of the practical effects had been uncovered (and the reader is recommended to read *Natural Philosophy*, published by the Society for the Diffusion of Useful Knowledge, for a fascinating account of the then state of the art). Michael Faraday, working with marvellous intuition, was perhaps most responsible for these discoveries, but it was Kelvin following Weber and Gauss who insisted that current electricity could not be a science until measurement was possible. It was Kelvin who did more than any other to bring about the institution of the volt, amp, ohm, etc., as standards. It was the same with the subject of thermodynamics in which Kelvin and his friend, J. P. Joule, together produced a new science.

Discoveries were thick on the ground. Kelvin's lecturing was notoriously affected by the fact that he, while talking to students, would frequently be diverted by new thoughts that had just occurred to him! The position with respect to textbooks for students was particularly unsatisfactory. In 1867 Kelvin and P. G. Tait, of Edinburgh, produced their *Treatise of Natural Philosophy*

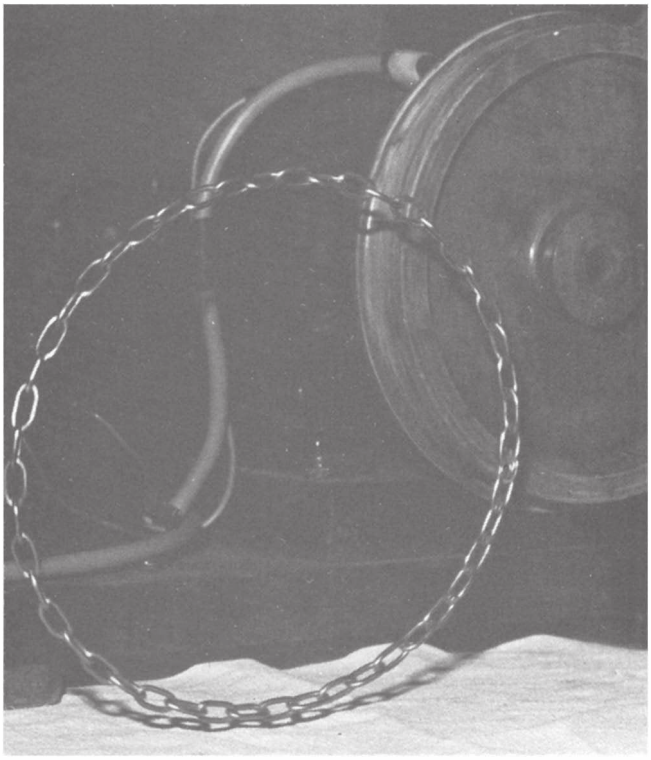


Fig. 2. The rigidity of a rotating chain.

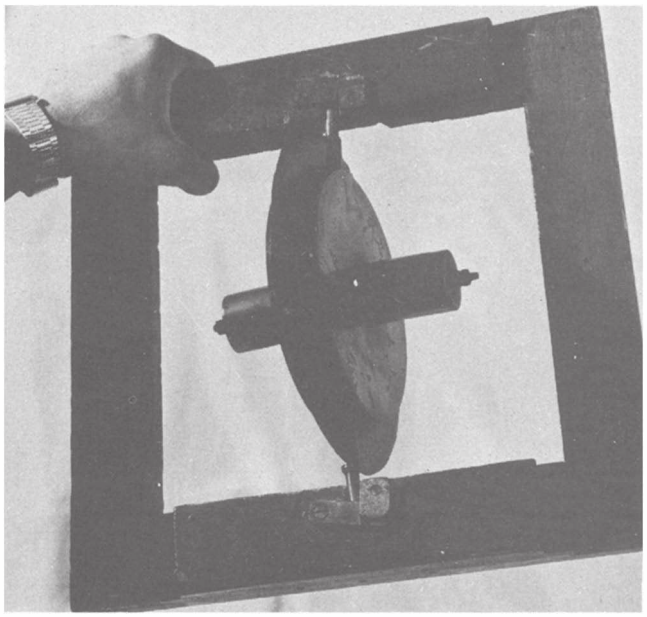


Fig. 4. Gyrostat in frame.

Fig. 3. Kelvin's precessional model of the world. The globe, supported at the center of gravity, shows the precession of the equinoxes by the shaft pressing against and rolling around the limiting ring.

(called T and T′, alias Thomson and Tait) which proved to be a milestone in the upward journey towards good textbooks.

Having covered Kelvin's background and motivation with regard to teaching, I would like now to describe some of his more effective demonstrations.[1] His actual mode and performance as a lecturer I will leave until the epilogue.

Kelvin's first love was for mechanical things and, in particular, the action of rotating bodies. One of his most stimulating demonstrations was of the simplest possible nature: it employed only a few eggs. It starts off with Columbus boasting that all things are possible, even balancing an egg on its point. "But, ah," says Kelvin, "he would have done better if he had *spun* the egg . . . but only if the egg were hard-boiled." Then he would produce such an egg, spinning it on its side, showing that it reared up on to its point into the "sleeping" position. He would show an unboiled egg, try to spin it, actually do so on its side, stop it momentarily with his finger and show by its subsequent rotation that the yoke had continued to rotate. There is a lot of good physics in these simple operations, and good fun too, particularly if some wily student had exchanged the boiled for an unboiled egg before the lecture began. And there were eggs for lunch in the Kelvin house that day!

Kelvin's ability to extract a lot from very simple things contributed a great deal to his success. He would demonstrate inertia by tapping out the lowest coin from a pile which he had taken from his pocket; he showed the quasi-rigidity of rotating flexible bodies by rotating a sheet of paper at high speed and tapping it with his cane (he had broken his thigh while "curling" on the ice in 1861 and henceforth limped quite badly, requiring the use of a

Fig. 5. The pyramid of gyros. Variant by Gray. If the support spindle is rotated in the same direction as the gyros the pyramid "goes to sleep" vertically. A very tense demonstration.

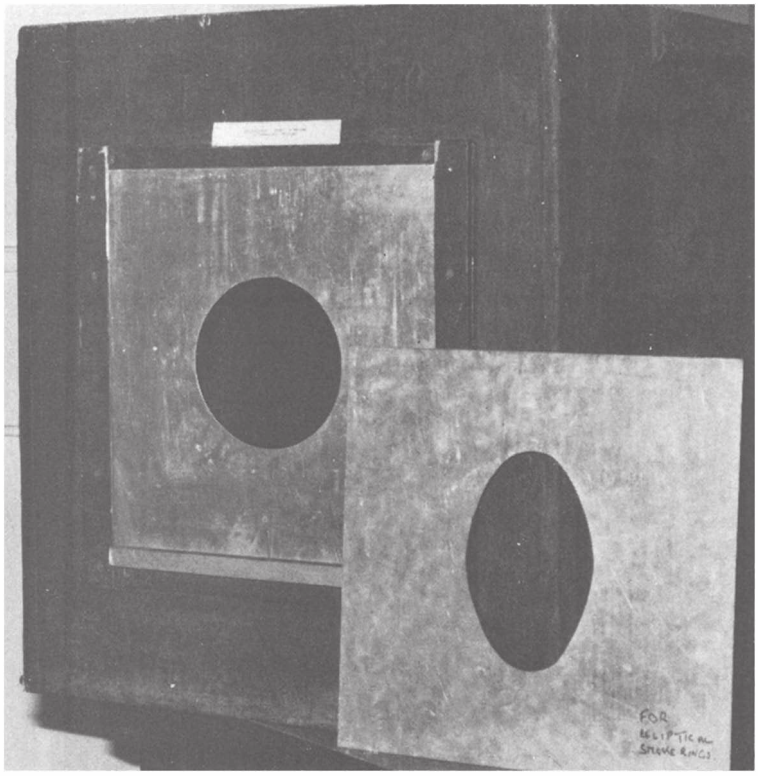


Fig. 6. Kelvin's smoke ring box (six inch rule included).

walking cane). His rotating-chain experiment was very nice. The chain shown in Fig. 2 is rotated on the edge of a wooden disc of about 8 in. in diameter – I use a speed of about 1800 rpm, but probably an even higher speed would be better. The chain is dislodged from the edge by using a blade of metal, and this has to be done carefully and slowly, for sometimes the chain goes backwards sharply. On the bench below the wheel is draped a cloth: when the chain hits the surface it starts to travel at high speed and if it hits a low obstacle it bounds into the air and bounces on coming back to earth. Kelvin also liked to show his model of the precessing world (Fig. 3). He would show it precessing through a complete circle – "And now, gentlemen, 26 000 years have elapsed!" His "gyrostat" (Fig. 4), in a gimballed frame, used to be handed to a student. Held horizontally, and swung round in the extended hands in the same direction as the gyro was rotating, nothing happened – but on swinging in the opposite direction the gyro convulsively heaves through 180°, giving the holder a nasty turn indeed! Kelvin's joke was – "I would like to fit one of these secretly under a waiter's tray and watch him as he tries to hand out the drinks." One of Kelvin's prettiest demonstrations was the "pyramid of gyros." Apparently he could support three gyros, one on top of the other, on his finger. He certainly must have been very clever to do this – and he certainly would not have done it with the gyros shown in Fig. 5. The latter were the products of his successors, Andrew and James Gray, who specialized in the subject, and they rotate at about 15 000 rpm accompanied by a lot of noise and some danger.

On the same theme of rotational behavior there are a number of smoke-ring experiments which are both entertaining and inspiring. Kelvin's smoke-ring box is very large – Fig. 6 (I must say that all of Kelvin's experiments fulfilled the first requirement of a good demonstration – they should be seen easily). The apertures, which are 7 in. in diameter, slide into grooves at the front of the box. The box is filled with smoke admitted through holes in the side, the aperture being capped, temporarily, with a sheet of cardboard. For smoke Kelvin apparently used air passed through strong ammonia and nitric acid bubblers, but I have never done this, feeling it to be a little antisocial to

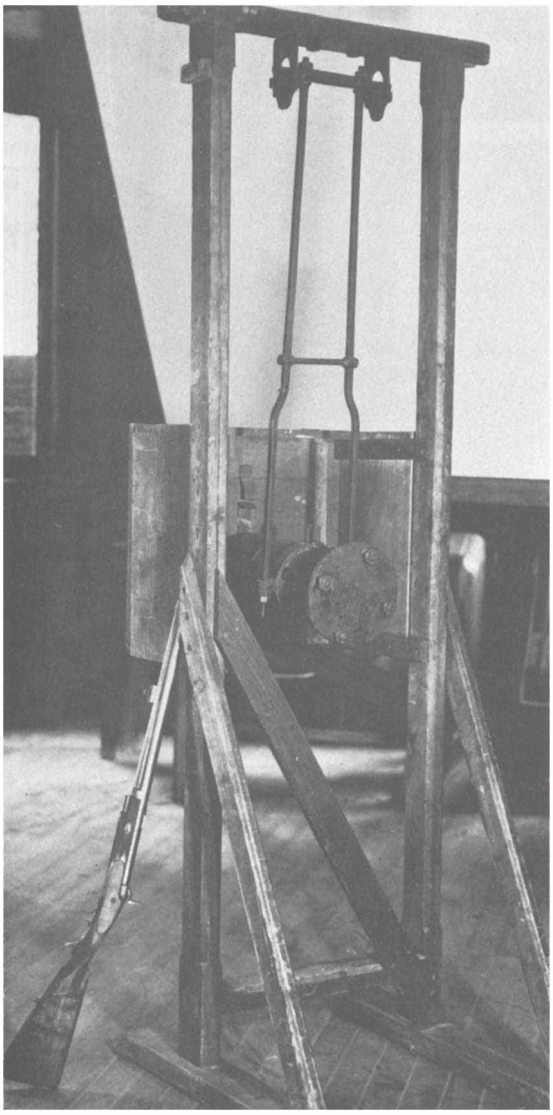


Fig. 7. The elephant gun and the Robin's ballistic pendulum, rear view.

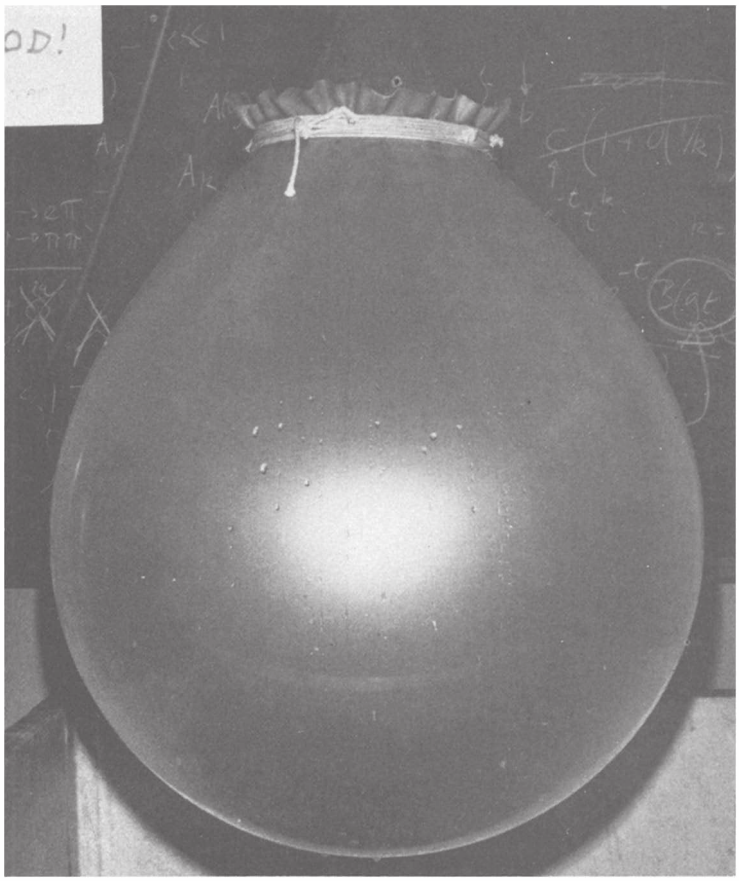


Fig. 8. The "trembling dewdrop." A drop weighing 200 lbs. (Photographed here at a one day exhibition to celebrate the 250th anniversary of the Chair. The rubber used was 1/16 in. thick. Thinner rubber would improve the shape.)

spread such fumes around. Personally, I like to use tobacco smoke. I have a clay pipe with a large bung on the stem and I light this, showing much enjoyment, before starting the smoke-ring demonstration. The pipe is then inserted, bowl first, into a large tube and the far end of this tube blown into so that smoke issues from the stem.[2]

I must say at this point that I preface the demonstration with rings without smoke. The aperture is aimed at a lighted candle some 15 ft away and, if the aim is good, the candle is extinguished. Secondly the box is aimed at a part of the audience and this is quite effective because nothing happens immediately when the membrane is smacked – but a second or so later the hair or clothing is disturbed, in a ghostly fashion, as the vortex collides. The actual demonstration is very good: the circular smoke rings, illuminated from behind the box by a projector beam, the room being dark otherwise, proceed across the lecturing area with majesty. A hard surface may be interposed to reflect the rings. An even nicer effect can be produced from an elliptical aperture. The ring oscillates, axis to axis, as it progresses. I gather that Kelvin did another thing, which I have never tried, and that is to project *half* a smoke ring. He did this by putting a partition across the box, bisecting the aperture and thus producing a ring in which smoke was circulating in only half of the circumference. Smoke-ring making was very popular in the 1860s-1870s, and it was at this time that Kelvin evolved his "vortex atom" theory – that particles might be vortices of energy and would show rigidity and elasticity. Kelvin's friend P. G. Tait, some of whose correspondence we have in the Glasgow University Library, also had an interesting repertoire.In one letter he suggests using a miniature box filled with inky water, submerged in a trough of clear water. The ink rings thus produced are very beautiful but the experiment might be improved if bleach is added to the bulk of the water. Of course, television is essential to show this to a large audience.

There are two other experiments associated with Kelvin which are in the grand manner. The first simply demonstrates momentum, the determination of the velocity of a rifle bullet in class. We still have the Robin's ballistic pendulum used by Kelvin, Fig. 7; it is a tall structure from which, on knife edges, is supported a large metal pipe, filled with lead and with a plug of wood at the entrance. And we still have the elephant gun, muzzle loading and complete with a hand mould for making the lead bullets.

Before firing the gun Kelvin used to pack cotton wool in his ears and advise his students to do the same. The roar must have been gigantic in the classroom, but no one living has heard it. We are not allowed to fire it. One of the most memorable experiments I ever saw was this, performed by P. I. Dee, professor of natural philosophy from 1943 to 1973, at the Quincentenary Lecture in 1953. He used a service rifle, knelt and fired carefully at the bob. There was a loud bang from the gun, and the pendulum duly oscillated. There was also a loud crash from behind a curtain where someone had dropped a heavy weight into a metal bin full of glass, to add to the realism. But there were also two thuds on the adjacent bench; these were due to two dead pigeons which had been concealed, unknown to Professor Dee, in the 50-ft high ceiling of the lecture theatre, and released magnetically. Very elaborate, one might say, but I still meet people who remember the occasion with great pleasure.

The other spectacular was one which Kelvin always performed on the last day of term. It is called "the trembling dewdrop," and since his dewdrop contained up to 200 lbs of water, and the culmination of the experiment is that the drop bursts, it will be well understood why it is the last thing shown! The apparatus consists of an inverted metal funnel supported from a sort of gantry, 7 ft high. A stretched membrane of rubber is tightly bound across the face of the funnel, which is 10 in. in diameter, and to the spout is soldered a metal pipe about 4 ft high. Underneath is a large trough, about 4 ft cubic. Kelvin used to have a further funnel on top of the spout and a step ladder up which a man kept running, carrying buckets of water. All very hectic! Nowadays we just run in a rubber tube from a tap (Fig. 8).

The membrane first assumes a hemispherical shape; it swells soon to be spherical; it grows and becomes more pendulous; it becomes ponderous. Kelvin used to push it with his cane to make it oscillate. By the time it is about 20 in. in diameter it can be pushed upwards: it then heaves up and down with all the majesty of a mirthful elephant. Kelvin was apparently very adept at pointing underneath to the distortions on a grid which he had marked on to the rubber beforehand – and at moving back just before the rubber burst. I am afraid that I, myself, have been drenched on more than one occasion. The experiment always ends with incredulous laughter and cheers. I do not do it very often.

Kelvin was very fond of demonstrating the properties of cobbler's wax, or pitch. He compared it with the "ether," the possible presence and constitution of which was of deep interest to him. He pointed out that pitch, like the ether, had a certain dual property; fashioned like a bell it could ring (could transmit high frequencies) but it also allowed the slow movement, through it, of solid matter. In the classroom there was always a bowl of pitch, with wooden objects floating in it and metal objects sinking. In the Kelvin Museum we have the venerable "pitch glacier" which he started in 1887. It consists of wooden steps on top of which he placed a slab of pitch. The glacier is, by now, fully mature (Fig. 9).

Kelvin's teaching in current electricity has left no mementos – other than a museum full of his invented instruments! His optics lectures were always, it seems, a very hasty course, indeed it was only when he gave a famous series of lectures on the wave theory of light, in Baltimore in 1884, that he seems first to have perceived the real beauty of the subject. I think that his lectures on acoustics were probably quite memorable. He was a very keen musician and we have many of the instruments, including his French horn, with which he used to illustrate his lectures.

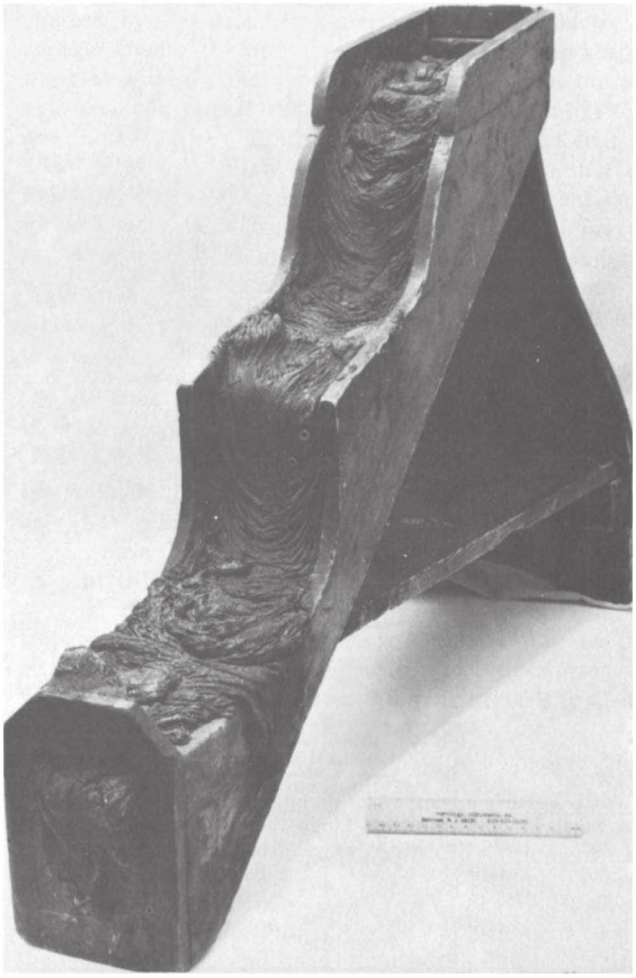


Fig. 9. Kelvin's pitch glacier, started 1887.

One subject which received special attention was electrostatics. The lecture cupboards have a good collection of instruments, many from the 18th century, including several types of machines, a Coulomb balance made by Pixii of Paris, early Leyden jars, electric cannon[3] and "electric egg."[4] Kelvin had on permanent show in the classroom one of his electrometers connected to a copper ball attached to the outer wall. Students were encouraged to keep a watch on the state of the atmospheric electricity; the electrometer was also occasionally connected to a water dropper supported on the roof. This brings me to a description of a machine which Kelvin showed on special occasions but probably not in class: his water-dropping electrical machine.

I had always been aware of the water dropper, of

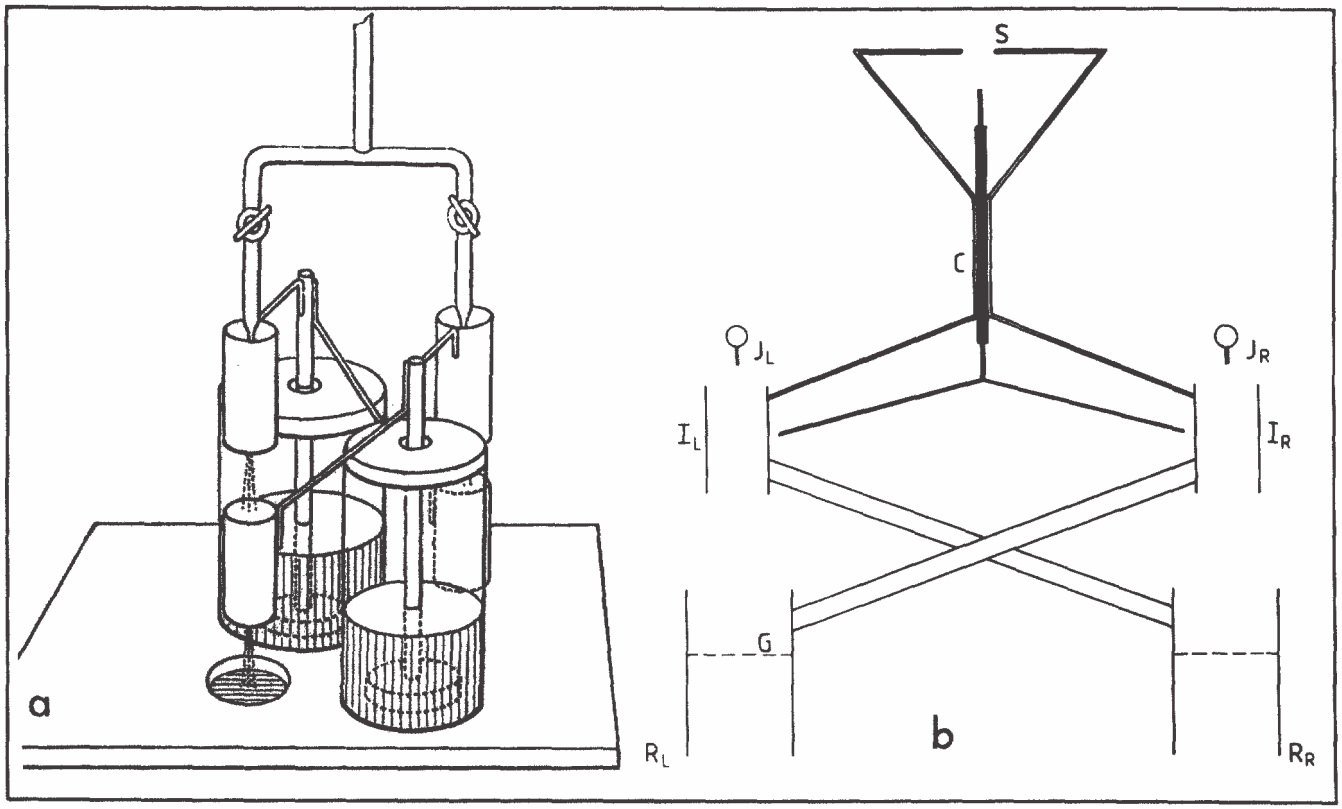


Fig. 10a. Kelvin's original water dropper machine, 1867. **10b.** Practical water dropper, the basic Lloyd variant. If the inductor I_L is charged +, it will induce a − charge on drops falling into the receiver R_L. I_R, joined to R_L, is also charged −, inducing a + charge on drops falling into R_R. The capacitor C is charged up by this 100% feedback process.

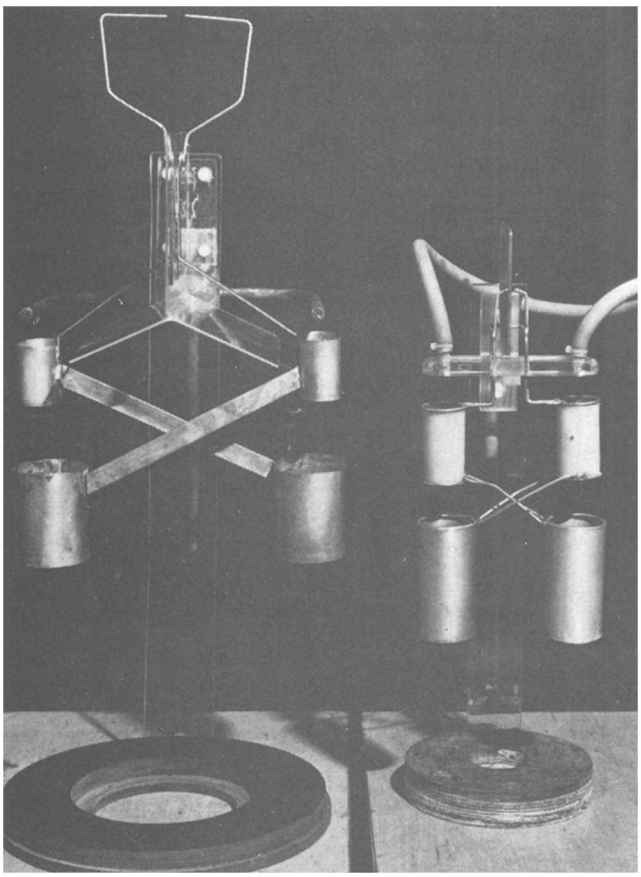


Fig. 11. Simple model(s) of the water drop, giving about 1-cm spark.

course, but Kelvin's own model has not survived and I had thought the instrument to be of only slight interest. However about two years ago we were visited by an American professor, Thomas B. Greenslade, Jr. of Kenyon College, Gambier, Ohio. I remember this with particular pleasure. We discussed, among other things, the Kelvin water dropper: I had nothing to show and became privately determined to rectify that situation! I looked at Kelvin's plans anew and saw that, transformed to modern materials, the device could be made to be very effective and even to be aesthetically beautiful, because of its symmetry and simplicity. And so I made a small one; then a larger one and so on. At the last count I have made six, after each one swearing it would be the last but each time something new occurred to me. I have latterly had a distinct foreboding because at times I find myself brooding over the possibility of making an electrostatic fountain for the garden!

Kelvin, in his original machine, used Leyden jars which contained concentrated sulphuric acid and probably were very good (Fig. 10a). The modified design uses Lucite as the dielectric for the capacitor and every part of the machine is supported from this capacitor, Fig. 10b. This feature plus the addition of a spray shield ensures as much as possible that the vital insulation is not affected by the water. The main materials for constructing the machines include the following. The Lucite insulation is 1.5 mm thick. The water jets are made from a few millimeters of hypodermic tubing, of bore 0.6 mm. For the metal parts I use copper tube quite a lot, either in the round or flattened condition; this has a bore of 6 mm and a wall thickness of 1 mm. I also use copper or other metal sheet, with the edge folded over. It is important not to have sharp edges on any of the metalwork. The gauze platform, used in the re-

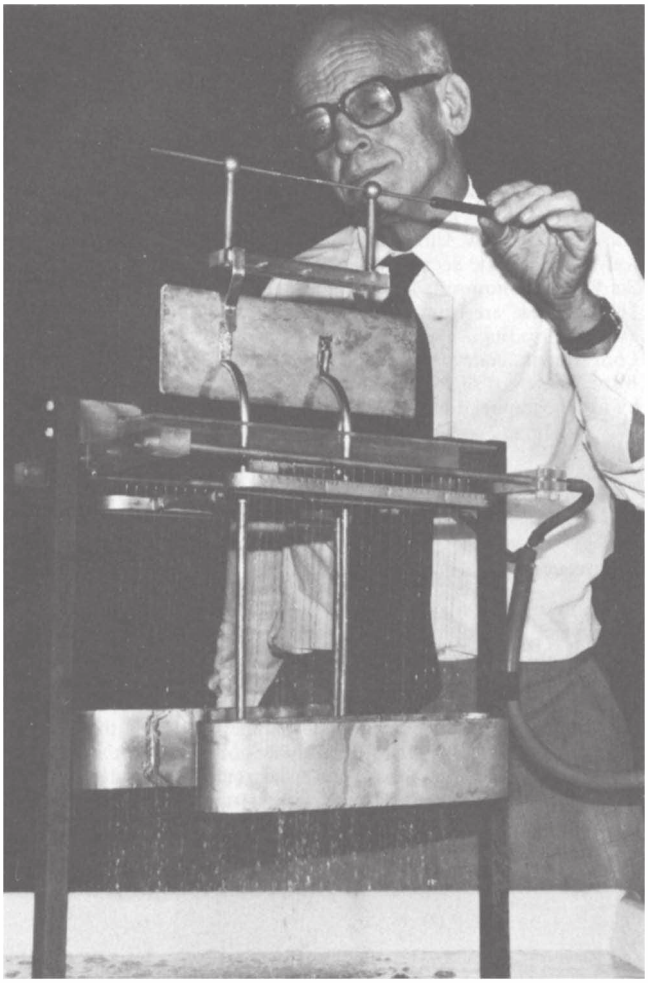


Fig. 12. The "thunderstorm machine," giving up to 2-cm spark. Plastic skirts and adequate drainage are essential.

ceivers, has 20 strands to 1 cm. All of the machines seem to spark at the same rate, from 3 to 5 sec. They have rarely been affected by humidity, in fact only once have I been driven to use a hairdrier on them to get them started. The power of the spark is, of course, dependent on the capacity and also on the rate at which the water droplets flow. Practically all of the machines have each a number of jets which can be clustered or spaced as closely as 2 mm apart. One point of interest is that the jets deflect apart as charge is built up. In the largest machine, the "thunderstorm machine," Fig. 12, there are 46 jets in all: the capacitor measures about 500 pF, the spark is up to 2 cm in length and it is vicious. The thunderstorm machine is very surprising indeed; there is so much water involved that one would not have expected it to work. To be quite honest I am perplexed; to see all of the jets playing on to two receivers that are some 20 kV apart seems quite impossible; perhaps it really is true that the gauze inside the receiver is at a very low potential – because the charge goes immediately to the outside of the vessel!

Kelvin himself describes the action in a much more succinct form than I can. He says (Proc. Roy. Soc., June 1867) "... reciprocal arrangement, in which the body charged by the drops of water is made the inductor for another stream, the drops from which in their turn keep up the charge of the inductor of this first." Perhaps the only difficulty concerns the small initial charge which has to be assumed to be present on one of the inductors. Kelvin got out of it rather nicely by promoting the idea that one inductor might be made of zinc and the adjacent jet of copper, thus giving a small potential difference. In practice the machines described are symmetrical arrangements, and while there might be some difficulty in starting them when new – and by that I mean that they might not start for a minute or two – there is almost always no trouble subsequently, because of the residual charge.

I think the machines are more instructive than the Van de Graaff; they are certainly very surprising and have the simplicity which is so desirable in a good machine. Incidentally the water dropper is regarded as the first ancestor of the Van de Graaff.

I have mentioned previously that Kelvin, in lecturing, was apt to speak above his students' capability of understanding. This was exacerbated by a peculiarity in the Glasgow system, that students of divinity had to take Nat. Phil. as one of their subjects – and, of course, they were mainly not very interested in it. Although these students formed the larger part of the first year class, there was no doubt that Kelvin tended to lecture to the level of those who were to continue in physics. He did have a device which was very effective in inducing an interest in what he had to say; this was called "the Purgatory Box" (Fig. 13). The box was produced each day and it has three compartments – Purgatory, Heaven and Hell. He used to pick out names on slips from "Purgatory," ask questions of each of the named persons and finally deposit the slips in "Heaven" or "Hell" as the answers deserved.

Despite these stories I believe that to the earnest student of physics Kelvin was a highly effective lecturer. Various very intelligent people have left us in no doubt about this. David Murray, who was a student in Nat. Phil. in the late 1850s, has the following to say about him (in his book – *Memories of the Old College of Glasgow*) – "Lord Kelvin possessed the gift of lucid exposition in ordinary language remarkably free from technicalities. Occasionally he got out of the range of the majority of his class, but there was no obscurity in his statement, it was simply beyond their grasp," "He ... used no notes in lecturing." "He was always in earnest, and when dealing with great problems, spoke with the fervour of a missionary charged with a weighty message." "It was a strange sight to watch him as he became more and more eager in his exposition; a light seemed to play upon his forehead like an emanation." "His was a unique personality; genius of the highest order coupled with sound judgement and practical ability; passionate earnestness and deep reverence; a modesty and simplicity of character seldom met with." Fulsome praise, indeed!

There is, of course, the complementary side of teaching – practical laboratory work – to be considered. Kelvin is reputed to have started the first ever practical classes in physics, in 1848. It seems, however, that Kelvin used the "Laboratory Corps" to assist him in his own researches – a very satisfactory arrangement for the professor and clearly a very privileged opportunity for the students. Some very famous people went through Kelvin's laboratories.

Recently we had the pleasure of discovering that one of his laboratory students in 1887 was Gerard Philips, researching on instrumentation and the calibration of "incandescent lamps." It was he, with his brother, who founded the firm Philips Gloielampenfabrieken of Eindhoven, which apparently is the largest firm in the world, outside the United States.

Finally, I have to report that a remarkable thing has happened recently: a gramophone record made by Lord Kelvin and kept, unknown to us, in the depths of the British Museum, has been unearthed by the efforts of a student in – believe it or not – Tasmania. The Kelvin Museum has been given permission by the British Museum to hold one copy. Kelvin, on this early disc, and in the final year of his life, is giving a reading from a Philosophical Magazine paper of his, describing a possible explanation of the radioactivity of the heavy elements (founded, again, on mechanical principles).

I can,therefore, say the following with assurance. Lord Kelvin spoke with a fairly pronounced Scottish accent – although some people agree with me that there is a little Irishness in his speech. His articulation is good, especially so considering his great age and the primitive nature of the recording. He obviously had a great expositional style and there is authority and positiveness in every syllable he utters. It is sad that his theory of the atom – the "plum pudding atom" – was not the correct one but at least we can say with certainty, now, that Lord Kelvin was a great speaker – and a great teacher.

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2. There is some mystique in the manner in which the opposite, canvas side is struck; this can only be got by practice.
3. A large brass cannon that fired a charge of gun powder.
4. An egg-shaped glass vessel with electrodes, which could be evacuated.

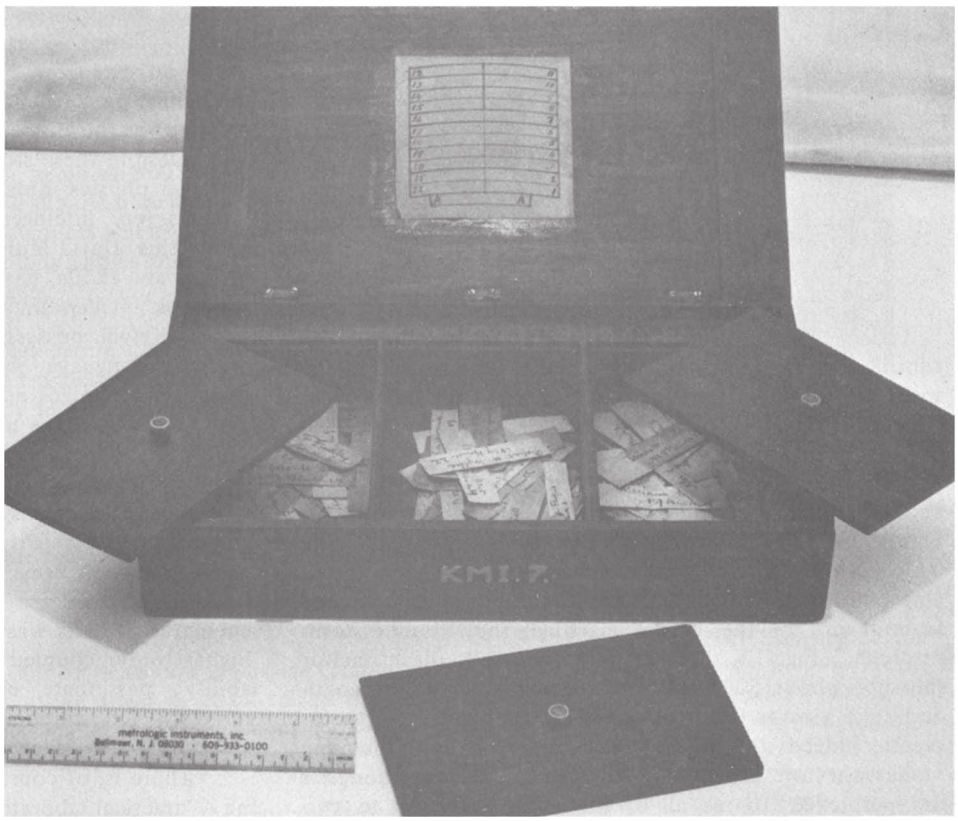

Fig. 13. Kelvin's Purgatory Box. Used for daily examinations.